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Strontium isotope evidence for human mobility in the Neolithic of northern Greece

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Abstract

Strontium isotope ratios are widely used in archaeology to differentiate between local and non-local populations. Herein, strontium isotope ratios of 36 human tooth enamels from seven archaeological sites spanning the Early to Late Neolithic of northern Greece (7th-5th millennia B.C.E.) were analysed with the aim of providing new information relating to the movement of humans across the region. Local bioavailable $^{87}Sr/^{86}Sr$ signals were established using tooth enamel from 26 domestic animals from the same Neolithic sites. $^{87}Sr/^{86}Sr$ values of faunal samples correlate well with predicted strontium isotope ratios of the local geology. This is consistent with animal management occurring at a local level, although at Late Neolithic sites strontium isotope values became more varied, potentially indicating changing herding practices. The strontium isotope analysis of human tooth enamel likewise suggests limited population movement within the Neolithic of northern Greece. Almost all individuals sampled exhibited $^{87}Sr/^{86}Sr$ values consistent with having spent their early life (during the period of tooth mineralisation) in the local area, although movement could have occurred between isotopically homogeneous areas. The strontium isotope ratios of only three individuals lay outside of the local bioavailable $^{87}Sr/^{86}Sr$ range and these individuals are interpreted as having spent their early lives in a region with a more radiogenic biologically available $^{87}Sr/^{86}Sr$. Mobility patterns determined using Sr isotope analysis supports the current evidence for movement and exchange observed through studies of pottery circulation. Suggesting limited movement in the Early and Middle Neolithic and greater movement in the Late Neolithic.

Keywords
Strontium isotopes, Neolithic, Greece, Mobility, Human, Animals

Highlights

- Sr isotope ratios were determined for 36 human and 26 faunal tooth enamel samples
- Seven sites spanning the EN to the LN of northern Greece
- $^{87}Sr/^{86}Sr$ values of human tooth enamel shows that population movement was limited
- Three individuals identified as 'non-locals'
- Sr ratio of faunal enamel infers animal management occurred on a local level

1. Introduction

The application of strontium isotope analyses to archaeological skeletal remains can provide information regarding the movement of humans and animals by comparing the strontium isotope signature of an individual to the biologically available signature determined by the surrounding biosphere (Bentley, 2006). Given suitable variation in the biologically available signatures in a region, strontium isotope ratios are able to differentiate between local and non-local populations. This can be used as complementary evidence to that obtained from the traded and exchanged goods, identified through material cultural remains, which together can provide a record of movement and exchange networks across a region. Strontium isotope analyses have thus been widely utilised to explore the mobility of early Hominins (Balter *et al.*, 2012), Pliocene mammals (Hoppe *et al.*, 1999), Neanderthal populations (Britton *et al.*, 2011) and Pre-historic human and animal mobility (Grupe *et al.*, 1997; Viner *et al.*, 2010; Bentley, 2013; Boric and Price, 2013; Giblin *et al.*, 2013; Gerling, 2015; Henton *et al.*, 2017).

Evidence for movement and exchange has been identified in the Greek Neolithic from the movement of material culture, including pottery, stone tools and shell ornaments. The study of fine-decorated pottery assemblages has shown that the circulation of pottery in northern Greece was very limited (Pentedeka, 2011; Urem-Kotsou *et al.*, 2012). Due to the low amount of pottery found in the Early Neolithic (EN) it is difficult to ascertain if exchanges of pottery took place (Perlès and Vitelli, 1999). However, indications of pottery exchange, in the form of imported pottery is found in the Middle Neolithic (MN) where stylistic developments were shared, and small-scale exchanges took place (Perlès and Vitelli, 1999; Pentedeka, 2011; Urem-Kotsou *et al.*, 2012). Analogous traits between vessel technology, shapes and cultural styles infers networks of communication and exchange operational on regional and inter-regional levels at this time (Çilingiroglu, 2010; Dimoula *et al.*, 2012; Urem-Kotsou *et al.*, 2016). Analysis of lithics from across the period have shown that stone tools were produced in the vicinity, from locally sourced raw materials (Perlès and Vitelli, 1999; Pentedeka, 2011). In the late Neolithic (LN), common pottery wares (black burnished and red slipped) are widespread, thus making it difficult to determine if the pots are locally produced or exchanged (Perlès and Vitelli, 1999). Widespread distribution of materials with limited production sites, such as obsidian, flint and jasper have been identified in the LN (Perlès and Vitelli, 1999; Milić, 2014) as have the movement of stone and spondylus shell ornaments, which circulated over large distances (Pentedeka, 2011; Veropoulidou, 2012). This demonstrates contact between human groups, however, given the small sample size and the number of sites and locations, any suggestion of diachronic change should arguably be made more cautiously. In contrast, $^{87}Sr/^{86}Sr$ values from human and animal teeth can be used to infer mobility over longer distances.

Thus far, the use of strontium isotope ratios to identify mobility during the Neolithic of Greece has been restricted to Crete. This small scale study demonstrated that mobility in Crete during the Neolithic was limited or that movements occurred between areas of homogenous underlying geology (Triantaphyllou *et al.*, 2015). To date, no isotopic studies have been conducted on other Neolithic Greek assemblages and aside from movements identified through material culture (Perlès, 2001; Urem-Kotsou *et al.*, 2012; Triantaphyllou *et al.*, 2015) little is known about human mobility in northern Greece. A greater number of mobility studies using strontium isotope ratios have been conducted on Bronze Age tooth enamel and modern reference material from sites situated in the southern Greek mainland and Crete (Nafplioti, 2008; Nafplioti, 2009, 2011). Consequently, this study of strontium isotope analysis on human tooth enamel aims to shed light on the extent of mobility throughout the Neolithic of northern Greece.

The study area in the central and western regions of Greek Macedonia comprises fertile basins separated by mountain ranges. Three broad NE-SW trending geographical ranges give rise to three geological zones bounded by faults which share a common history of deposition and formation (Higgins and Higgins, 1996). The western Pelagonian zone, comprising Triassic and Jurassic limestones and marbles deposited over gneiss. The central Vardar zone, once part of the Tethys Ocean, is made up of Mesozoic deep-water sedimentary and ophiolites, occasionally overlain by limestone and Eocene sediments. The eastern Serbo-Macedonian massif is dominated by metamorphic and plutonic rocks uplifted and faulted by Alpine compressions (Higgins and Higgins, 1996).

Strontium isotope analyses were performed on 36 human tooth enamel samples from seven archaeological sites spanning the Early to Late Neolithic of northern Greece (Fig. 1). The sites in this study were chosen to chronologically span a large period of the Neolithic and, in addition, cover a range of geographical environments and terrains from coastal to inland locations and fertile basins to mountainous localities (Fig. 1). This allowed temporal study of mobility and comparisons between settlements which are in geographically close proximity with those that are spatially apart. The majority of the human remains studied comprise single burials with minimal grave goods located within the settlements (Triantaphyllou, 2001; Bessios *et al.*, 2003; Triantaphyllou, 2008; Ziota *et al.*, 2009). However, at two of the study sites, Stavroupoli and Toumba Kremastis Koiladas, human burials comprise disarticulated remains and articulated burials are rare (Chondrogianni-Metoki, 1999; Triantaphyllou, 2002, 2004, 2008); at Toumba Kremastis Koiladas many of the dead were cremated (Chondrogianni-Metoki, 2009).

Given the complexity of the regional geology, it is difficult to accurately predict the bioavailable $^{87}Sr/^{86}Sr$ values in the vegetation local to each Neolithic site. For LN Makriyalos, values estimated from modern vegetation samples (of deep-rooted trees and ground vegetation, n=20), collected from within 15 km of the archaeological site and determined by Vaiglova et al. (in preparation), were used for this purpose. These values are also extended to and combined with the information from geographically and geologically similar sites of Revenia and Paliambela to establish a local $^{87}Sr/^{86}Sr$ ratio. For six other sites, bioavailable $^{87}Sr/^{86}Sr$ values were estimated from samples of tooth enamel from archaeological specimens of domestic animals recovered by excavation. Cattle were excluded as they have been shown to be herded over long distances through-out Europe during the Neolithic (Knipper, 2009; Towers *et al.*, 2010; Viner *et al.*, 2010; Sjögren and Price, 2013; Gerling *et al.*, 2017). For this reason, teeth of sheep, goats and pigs were selected where possible for the estimation of locally bioavailable Sr values. There is a possibility that these species can be transhumant; seasonal movement of ovicaprids has detected throughout prehistory (Bocherens *et al.*, 2001; Henton, 2012; Makarewicz *et al.*, 2017; Makarewicz and Pederzani, 2017) however, this is not always the case (Bogaard *et al.*, 2014; Gerling *et al.*, 2015; Marciniak *et al.*, 2017). In the Neolithic of Northern Greece there is no evidence for or against the adoption of transhumance for sheep/goat and we will have to experimentally determine (by way of agreement with either pigs or cows) whether this behaviour is practiced and therefore whether they can for these sites be a local reference.

2. Materials and Methods

Sample preparation, Sr purification and isotope ratio measurement closely follow the procedures outlined in Haak *et al.* (2008), Lewis *et al.* (2014) and Lewis *et al.* (2017). Sample preparation and analyses were conducted in the Bristol Isotope Group, School of Earth Sciences, University of Bristol, UK. The exterior of a tooth was cleaned with a stainless-steel grinding burr and a small piece of enamel (~10 mg) removed from the crown of the tooth using a diamond tipped cutting wheel and any dentine adhering to the enamel was removed. Enamel samples were then rinsed with ultrapure water (18.2 MΩ) and dried. Super high purity acids were used throughout the strontium chemistry and diluted to the desired concentrations using ultrapure water. Enamel samples were weighed into a clean PFA beaker and dissolved in 7M HNO_3, an aliquot of the sample equivalent to 3 mg of solid enamel was taken for ion exchange chromatography. Strontium was separated from the sample matrix using Sr Spec. resin (Eichrom 50 100 μm particle size; Horwitz *et al.*, 1992). Clean Sr Spec. was loaded on to 100 μL PFA micro columns for Sr separation, samples were loaded in 0.5 mL 3M HNO_3, sample matrix was eluted in 2 mL 3M HNO_3 and strontium was then collected in 1.5 mL ultrapure water.

Strontium isotope analyses were carried out using a ThermoFinnigan Triton Thermal Ionisation Mass Spectrometer (TIMS). Samples were loaded on to rhenium filaments in nitric acid form with 1 μL of tantalum pentachloride ($TaCl_5$) and 1 μL of 10% phosphoric acid following a modified version of Birck (1986). Triton amplifier gains were determined at the start of each sequence of analyses and all beams were collected on 1011 Ω amplifiers. Filaments were heated automatically, including source tuning, and analysis started once a beam current of 80 pA ^{88}Sr was reached. Faraday cups were set to collect ^{84}Sr, ^{85}Rb, ^{86}Sr, ^{87}Sr and ^{88}Sr as a static analysis and data was collected in 30 blocks of 12 cycles with a 4.194 second integration time per cycle. Samples were corrected for mass fractionation using exponential mass fractionation law and $^{86}Sr/^{88}Sr$ of 0.1194 (Nier, 1938; Russell *et al.*, 1978). ^{87}Sr beams were corrected for isobaric ^{87}Rb using the $^{85}Rb/^{87}Rb$ value of 2.59265 (Steiger and Jäger, 1977) which is adjusted for instrumental mass bias. All recorded values were normalised to a known standard NIST SRM 987 $^{87}Sr/^{86}Sr$ value of 0.710248 (Avanzinelli *et al.*, 2005). Long term reproducibility of NIST SRM 987 measurements made over the course of this study is 0.71022 ± 0.00005 (2SD; n=24). The reproducibility of a NIST SRM 987 passed through each batch of chemistry is 0.71024 ± 0.00001 (2SD; n=6) and modern marine shell measured with each batch of samples is 0.70916 ± 0.00004 (2SD; n=6).

3. Results and discussion

3.1 Establishing a local range of bioavailable strontium using faunal teeth.

'Bioavailable strontium' is the range of local strontium available to plants and animals within an ecosystem, which is delivered to the consumer with an accompanying $^{87}Sr/^{86}Sr$ isotope value (Bain and Bacon, 1994). Ecological studies have shown the strontium isotope ratio of terrestrial herbivores broadly reflects that of the surrounding bedrock values (Capo *et al.*, 1998). The local environmental strontium isotope ratio value is made up of terrestrial sources primarily from mineral weathering of surrounding bedrock and atmospheric strontium derived from continental dust and precipitation. At coastal locations sea-spray can also contribute to the local $^{87}Sr/^{86}Sr$ ratio values (Miller *et al.*, 1993;

Capo *et al.*, 1998; Vitousek *et al.*, 1999; Whipkey *et al.*, 2000). Human and animal tooth enamel from several sites appear to have values close to that of seawater (0.70918-0.79020; McArthur *et al.*, 2001). A sea-spray affect has been observed at distances of up to 50 m from the coast (Whipkey *et al.*, 2000) and on islands in the Outer Hebrides where biosphere samples reflected seawater strontium isotope ratio rather than the more radiogenic underlying gneiss and granite bedrock (Montgomery and Evans, 2006). As rainwater is derived from seawater, high levels of precipitation (>*c*. 2000 mm a^{-1}) can result in saturation of the soil and contribute to the bioavailable strontium pool (Evans *et al.*, 2010). The humans and animals from Revenia, Paliambela and Makriyalos situated a few km from the coast at the time of occupation (Pappa and Besios, 1999; Krahtopoulou and Veropoulidou, 2016) each display $^{87}Sr/^{86}Sr$ values close to that of seawater. At Stavroupoli the $^{87}Sr/^{86}Sr$ values of humans and animals are more radiogenic than that of seawater despite the close proximity of the site to the coast (ca. 3.5 km; Grammenos, 2006). The average rainfall for all settlements would be between 350-500 mm per annum (Panagos *et al.*, 2016), hence, high rainfall means that it is unlikely that the $^{87}Sr/^{86}Sr$ values are influenced by soil saturation.

The results presented in Table 1 show that, for the majority of sites, the $^{87}Sr/^{86}Sr$ values of Neolithic domestic animals fall within the predicted strontium isotope ratios of the surrounding geology, inferring that animal management most likely occurred at the local level. In fact, the $^{87}Sr/^{86}Sr$ values of the faunal samples are far less varied than the values estimated from the bedrock. The results also show there is no difference between the transhumant and non-transhumant species. This demonstrates that the local bioavailable Sr isotope baseline should ideally be determined from small fauna and plants, rather than extrapolating from bedrock as this is likely to underestimate the presence of 'non-local' individuals. The exception to this is the site of Stavroupoli, a LN tell site spread over 10 ha (Table 1). Here, the $^{87}Sr/^{86}Sr$ values of pig (0.71066), sheep (0.71113) and goat (0.71040), are consistent with the surrounding bedrock, which comprises Holocene coastal and Miocene lacustrine and terrestrial deposits. However, a more radiogenic $^{87}Sr/^{86}Sr$ value (0.71255) was determined for the cattle tooth which is consistent with both Cenozoic and Mesozoic metamorphic rocks located to the east of the site (Fig. 1). Mesozoic metamorphic and igneous rocks approximately 3 km east of the settlement, provide a nearby likely candidate for the more radiogenic bioavailable $^{87}Sr/^{86}Sr$ value. Although this distance is still very close to the site the more radiogenic Sr ratio observed in the cattle could be either a result of cattle grazing on pastures in an area of more radiogenic $^{87}Sr/^{86}Sr$ or animal management strategies such as movement between the coastal flats surrounding Stavroupoli and the slopes of the Mount Chortiatis to the east (which comprise Cenozoic and Mesozoic metamorphic rocks). The seasonal movement of animals between lowlands and mountainous regions has been observed elsewhere during the Neolithic in Europe (Balasse *et al.*, 2002; Bentley *et al.*, 2003; Bentley and Knipper, 2005; Gerling *et al.*, 2017; Makarewicz, 2017). Although it is difficult to be certain due to the very small sample size, it is also possible that the cow was not raised within the local geologic area and was perhaps brought to Stavroupoli through exchange. Cattle management strategies throughout the Neolithic have been shown to vary, possibly as a result of adaptation to the local environment. For example, in EN Scandinavia (Gron *et al.*, 2016) and LN Britain (Viner *et al.*, 2010) cattle have been shown to have been driven over long distances. There is also evidence of both local management of livestock (Giblin *et al.*, 2013) and transhumance strategies (Bentley *et al.*, 2003; Stephan *et al.*, 2012).

3.2 Mobility in the Neolithic of northern Greece

The strontium isotope analysis of human tooth enamel undertaken herein suggests that population movement within the Neolithic of northern Greece was highly restricted as almost all populations investigated have $^{87}Sr/^{86}Sr$ values consistent with individuals having spent their early life in the local area or moving between areas with similar geology and thus similar strontium isotope ratios. An example of the latter possibility is observed in the $^{87}Sr/^{86}Sr$ values of the humans from the sites of Revenia and Makriyalos which are in close geographical proximity and have similar bioavailable $^{87}Sr/^{86}Sr$, which could potentially mask movement between them.

During the EN there is little variability in human (average 2SD = 187 ppm; n=10) and faunal (average 2SD = 202 ppm; n=6) strontium isotope values. A similar trend is observed in the MN fauna (average 2SD = 146 ppm; n=4). Towards the LN, however, there is more variation in strontium isotope values for both the fauna (average 2SD = 687 ppm; n=14) and humans (average 2SD = 2607 ppm; n=26) possibly reflecting changes in subsistence strategies and mobility behaviour. For example, the variance apparent in the human strontium isotope values for LN Makriyalos could be a consequence of a larger variability in the faunal samples due to changes in herding strategies or movement of people from an area with a similar underlying geology with differing Sr isotope values.

3.3 Identification of non-local individuals in the sample populations

Strontium isotope analyses of human tooth enamel from the northern Greece Neolithic sites demonstrate that most of the individuals sampled exhibited $^{87}Sr/^{86}Sr$ values consistent with having spent their early life in the 'local' area, although movement could have occurred between isotopically homogeneous areas. However, there are a few instances where the $^{87}Sr/^{86}Sr$ values of the sample population deviate from the bedrock geology, implying that these individuals spent their early life outside the local area from which their skeletal remains were ultimately recovered.

A notable departure from the general trend of local origin is seen in the population from Kleitos. The site is located on Pleistocene lacustrine and terrestrial sediments. Jurassic and Cretaceous hills sit close to the north of the site (Fig. 1). The $^{87}Sr/^{86}Sr$ values of the local bioavailable Sr estimate at Kleitos are consistent with the upper range of Mesozoic sediments and lowest estimates of Cenozoic sediments and in broad agreement with a sediment source for the Pleistocene age lacustrine and terrestrial deposits (Voerkelius *et al.*, 2010). Consistent with the general trend for Neolithic northern Greece, five of the individuals investigated displayed strontium isotope values that lie within the local $^{87}Sr/^{86}Sr$ range determined by the faunal teeth, suggesting that all were resident in the area at the time of tooth mineralisation, or had travelled from an area with a similar bioavailable strontium isotope ratio. Interestingly, however, the strontium isotope ratios of three individuals from Kleitos lie outside of the local bioavailable $^{87}Sr/^{86}Sr$ range (Fig. 2). These three individuals are interpreted as having spent their early lives on a more radiogenic geology. The $^{87}Sr/^{86}Sr$ values of the possible migrants are consistent with values established for Lower Palaeozoic rocks (Voerkelius *et al.*, 2010). The closest Lower Palaeozoic rocks lie approx. 60 km the north and north-east. The tooth with the most radiogenic $^{87}Sr/^{86}Sr$ value (0.71467) comes from KL-1, an individual of 6 years of age and of unknown sex. Enamel was sampled from the mandibular premolar, which mineralises between 1.5 and 7 years (Logan and Kronfeld, 1933; Gustafson and Koch, 1974; Schroeder, 1991). This suggests that the child had lived in a different geologic environment for the majority of their young life. Individual KL-2, a male in his mid-30's to mid-40's in age exhibited a slightly less radiogenic $^{87}Sr/^{86}Sr$ value (0.71285). Enamel was sampled from the maxillary right 2nd molar, which mineralises between 1.5 and 7.5 years (Logan and Kronfeld, 1933; Gustafson and Koch, 1974; Schroeder, 1991). This indicates that the individual was also a non-local during infancy. The final sample, KL-6 is slightly more radiogenic than the local strontium range (0.71089), the individual is estimated to be 15 years of age and of unknown sex. Enamel was sampled from the maxillary left 1st incisor, which mineralises between 3 months and 6 years of age (Logan and Kronfeld, 1933; Gustafson and Koch, 1974; Schroeder, 1991). The interpretation for this individual is more nuanced. It is possible that this individual has had a variable diet with some strontium being sourced from the local area and some from a non-local source either as a direct function of mobility, imported foodstuffs or the individual may have been raised in a region of discrete geology with a bioavailable $^{87}Sr/^{86}Sr$ of ~0.7109. This value would be consistent with Cenozoic age sedimentary rocks.

The strontium isotope ratios of 5 individuals from Makriyalos lie outside of the determined local isotopic range (Fig. 2), but within the estimated $^{87}Sr/^{86}Sr$ values for Miocene age uplands to the west of the site (0.70901 to 0.71100; Voerkelius *et al.*, 2010). Makriyalos, Paliambela and Revenia sit approx. 2-3 km form the same Miocene age upland, so one might expect the biologically available strontium isotope ratios the sites to be similar (~0.7092 to 0.7096). This interpretation is supported by the analysis of modern plants used to determine the local bioavailable strontium isotope ratio in this study (0.70900 to 0.70974; Vaiglova *et al.*, in preparation) Teeth MAK-5, 6, 9, 10 and 12 all belong to adults, suggesting movement from an area of a similar geology after tooth mineralisation.

The strontium isotope values for the individuals at Nea Nikomedeia lie outside the estimated $^{87}Sr/^{86}Sr$ values for the area for Cenozoic sediments (0.70901 to 0.71100; Voerkelius *et al.*, 2010), but lie in the range predicted for Mesozoic geology (0.70701 to 0.70900), which is consistent with the sediments which form the alluvial plain. The geology surrounding Nea Nikomedeia indicates that the site sits on Pliocene and Quaternary rocks, with alluvial sediment deposits consisting of lacustrine silts and terrestrial clays (Fig. 2). The alluvial plain was formed during the Holocene by the deposition of sediment from four of the surrounding rivers from the Cretaceous and Jurassic uplands to the West (Bintliff, 1976) and thus the source of bioavailable strontium at the site. Although direct determination of local bioavailable $^{87}Sr/^{86}Sr$ values from local vegetation would be required to confirm this. Therefore, the individuals at Nea Nikomedeia have $^{87}Sr/^{86}Sr$ values consistent with individuals having spent their early life in the local area.

4. Conclusions

In this investigation strontium isotope ratios have been used to explore the movement of Neolithic people in the north of Greece. Baseline bioavailable $^{87}Sr/^{86}Sr$ values calculated from faunal tooth enamel were shown to fall within with predicted $^{87}Sr/^{86}Sr$ values of the surrounding bedrock, suggesting that animal management occurred on a local level, although differences in herd management practices became more evident through more varied strontium isotope values at LN sites, which is potentially indicating of changing herding practices leading to a larger variability in the strontium isotope values of the faunal samples. Analyses of human tooth enamel suggests that overall population movement within the region was limited as at almost all sites most individuals exhibit $^{87}Sr/^{86}Sr$ values consistent with them having spent their early life in the local area from where their remains were recovered; although the potential for movement between geologically homogenous areas exhibiting similar strontium isotope ratios must always be considered. The strontium isotope ratios of 3 individuals at Kleitos and lie outside of the local bioavailable $^{87}Sr/^{86}Sr$ range. These individuals are interpreted as having spent their early lives on a more radiogenic geology, providing evidence of mobility in Greece determined using strontium isotope ratios. The results determined using Sr isotope analysis strengthens the current archaeological evidence for movement and exchange observed through studies of pottery circulation. With both suggesting limited movement in the Early and Middle Neolithic and greater movement in the Late Neolithic.

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Figure 1

Geological map of the study area with the location of settlements. 1. Stavroupoli (LN), 2. Nea Nikomedeia (EN), 3. Paliambela (MN), 4. Makriyalos (LN), 5. Revenia (EN), 6. Kleitos (LN), 7. Toumba Kremastis Koiladas (LN) (base map from US Geological survey 1:1.5M world geology map, 2017).

Figure 2

Scatterplot displaying the variation of human and faunal $^{87}Sr/^{86}Sr$ values with the local bioavailable $^{87}Sr/^{86}Sr$ ratio through the EN to LN of northern Greece. The shaded area represents the local bioavailable $^{87}Sr/^{86}Sr$ range defined using strontium isotope ratios of the faunal teeth ($\bar{x} \pm 2SD$).

Figure 1

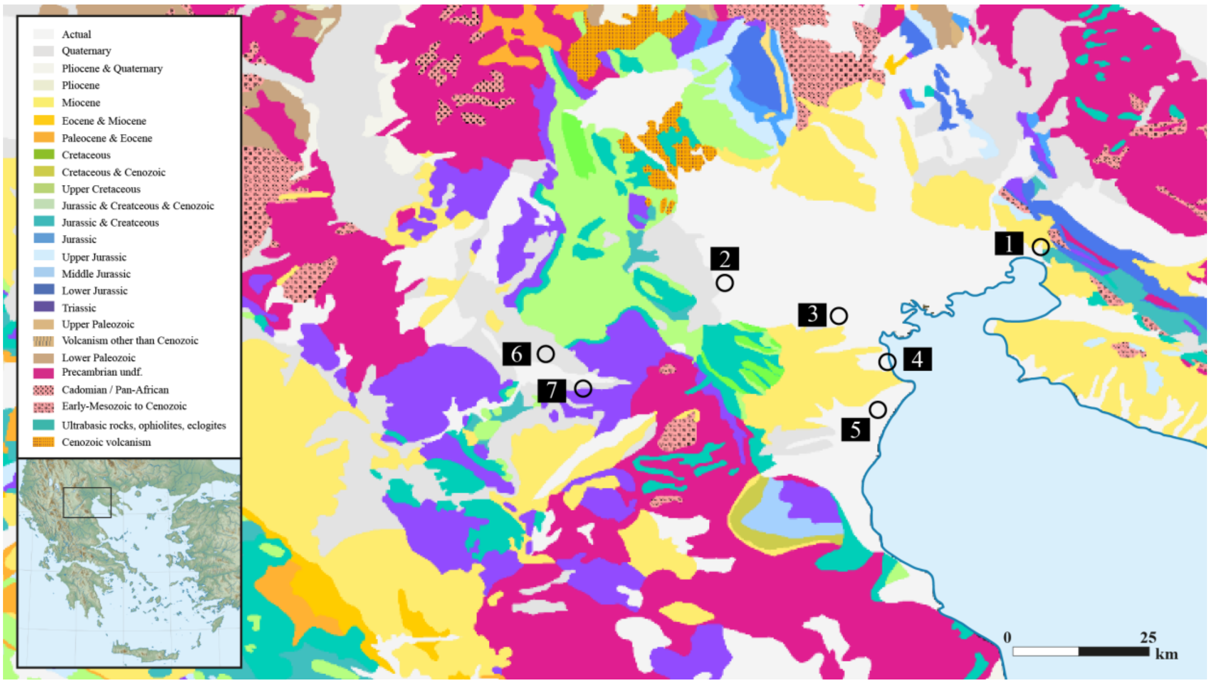
Actual
Quaternary
Pliocene & Quaternary
Pliocene
Miocene
Eocene & Miocene
Paleocene & Eocene
Cretaceous
Cretaceous & Cenozoic
Upper Cretaceous
Jurassic & Creatceous & Cenozoic
Jurassic & Creatceous
Jurassic
Upper Jurassic
Middle Jurassic
Lower Jurassic
Triassic
Upper Paleozoic
Volcanism other than Cenozoic
Lower Paleozoic
Precambrian undf.
Cadomian / Pan-African
Early-Mesozoic to Cenozoic
Ultrabasic rocks, ophiolites, eclogites
Cenozoic volcanism
1
2
3
4
5
6
7
0
25
km

Figure 2

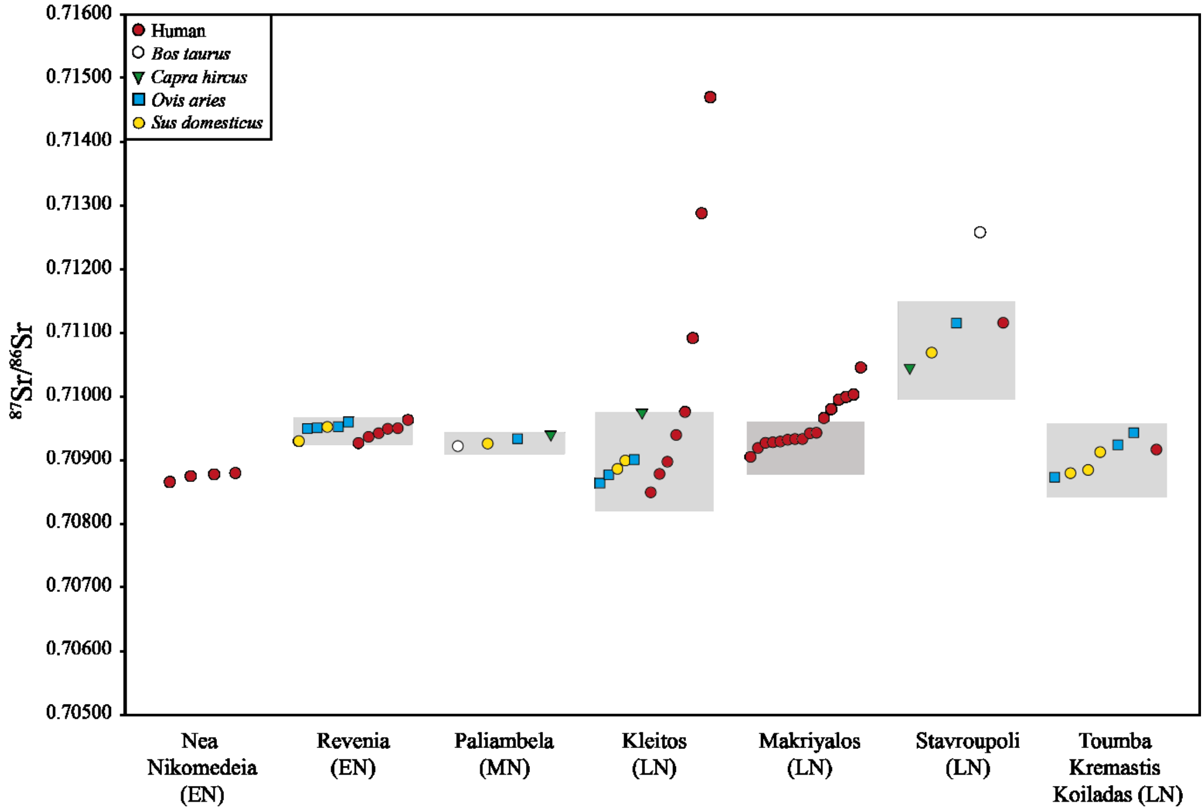
Human
Bos taurus
Capra hircus
Ovis aries
Sus domesticus
0.71600
0.71500
0.71400
0.71300
0.71200
0.71100
0.71000
0.70900
0.70800
0.70700
0.70600
0.70500
87Sr/86Sr
Nea Nikomedeia (EN)
Revenia (EN)
Paliambela (MN)
Kleitos (LN)
Makriyalos (LN)
Stavroupoli (LN)
Toumba Kremastis Koiladas (LN)

Table 1

Summary of the $^{87}Sr/^{86}Sr$ values for faunal and human teeth by site.

Table 2

Sample information and strontium isotope ratios for human archaeological tooth enamel

Table 1

Site	Faunal $\bar{x} \pm 2SD$	Bioavailable $^{87}Sr/^{86}Sr$ range*	Human $\bar{x} \pm 2SD$	Sediment source rocks	Predicted $^{87}Sr/^{86}Sr$ range***
Nea Nikomedeia	-	-	0.70872 ± 0.00012	Mesozoic sediments	0.70701 to 0.70900
Revenia	0.70947 ± 0.00020	0.70927 to 0.70967	0.70944 ± 0.00024	Pliocene and Quaternary sediments	0.70901 to 0.71100
Paliambela	0.70930 ± 0.00012	0.70917 to 0.70942	-	Cenozoic sediments	0.70901 to 0.71100
Kleitos	0.70898 ± 0.00076	0.70822 to 0.70974	0.71046 ± 0.00444	Cenozoic and Mesozoic sediments	0.70701 to 0.71100
Makriyalos	-	0.70889 to 0.70970**	0.70944 ± 0.00078	Cenozoic coastal sediments	0.70901 to 0.71100
Stavroupoli	0.71073 ± 0.00074	0.70999 to 0.71148	0.71113	Cenozoic lacustrine and terrestrial deposits	0.70901 to 0.71100
Toumba Kremastis Koiladas	0.70900 ± 0.00056	0.70844 to 0.70957	0.70914	Cenozoic sediments and Mesozoic metamorphic rocks	0.70701 to 0.71100

* in all cases except for Makriyalos, the range of values refers to estimates based on the local bioavailable $^{87}Sr/^{86}Sr$ range defined using strontium isotope ratios of the faunal teeth ($\bar{x} \pm 2SD$).

** range established using measured values of modern vegetation collected within 15 km of the archaeological site (Vaiglova *et al.* in prep).

*** Values from Voerkelius *et al.* (2010)

Table 2

Site	Sample	Tooth	Age (yrs)	Sex	$^{87}Sr/^{86}Sr$	±2 SE
Kleitos	KL-1	mandibular P	6.5-7	?	0.71467	0.00001
	KL-2	maxillary RM2	mid 30’s-mid 40’s	M	0.71285	0.00001
	KL-3	mandibular RP1	late 30's	F	0.70937	0.00001
	KL-4	maxillary RM2	30-40	M	0.70973	0.00001
	KL-5	maxillary RI2	40-50	F	0.70847	0.00001
	KL-6	maxillary LI1	15	?	0.71089	0.00001
	KL-7	mandibular RC	late 30's	F	0.70895	0.00001
	KL-8	maxillary RM2	17-18	M	0.70876	0.00001
Makriyalos	MAK-1	mandibular LM2	-	-	0.70903	0.00001
	MAK-2	mandibular RP2	-	F?	0.70925	0.00001
	MAK-3	mandibular LP2	-	-	0.70917	0.00001
	MAK-4	mandibular RM2	-	-	0.70927	0.00000
	MAK-5	mandibular RM1	18-30	M?	0.70997	0.00001
	MAK-6	mandibular RC	30-40	-	0.71001	0.00001
	MAK-7	mandibular LM2	-	-	0.70930	0.00001
	MAK-8	mandibular RI2	18-30	-	0.70941	0.00001
	MAK-9	maxillary LI1	18-30	-	0.70978	0.00001
	MAK-10	mandibular LP2	18-30	-	0.71054	0.00001
	MAK-11	mandibular RM1	18-30	-	0.70940	0.00001
	MAK-12	maxillary LM1	18-30	-	0.70993	0.00001
	MAK-13	mandibular RM1	-	-	0.70931	0.00001
	MAK-14	mandibular RM1	-	-	0.70964	0.00001
	MAK-15	mandibular RM1	-	-	0.70926	0.00001
	MAK-16	maxillary RM2	-	-	0.70931	0.00001
Nea Nikomedeia	NIK-1	molar	-	-	0.70872	0.00001
	NIK-2	molar	-	-	0.70875	0.00001
	NIK-3	molar	-	-	0.70877	0.00001
	NIK-4	molar	7-8	?	0.70863	0.00001
Revenia	REV-1	mandibular RC	12-13	?	0.70924	0.00001
	REV-2	maxillary LI1	33-35	M	0.70940	0.00001
	REV-3	maxillary LM3	40-50	F?	0.70946	0.00001

	REV-4	mandibular LP2	late 30's	F?	0.70947	0.00001
	REV-5	mandibular LC	40-50	F?	0.70943	0.00012
	REV-6	mandibular LP2	40-50	F?	0.70961	0.00001
Stavroupoli Toumba	STAV-5	premolar	-	-	0.71113	0.00001
Kremastis Koiladas	KK-7	premolar	-	-	0.70914	0.00001